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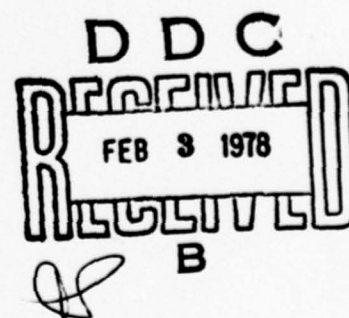
GROUTING OF SOILS IN COLD ENVIRONMENTS

A Literature Search

Robert Johnson

December 1977

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A literature search was undertaken to collect information on grouting of soils as related to low temperature environment, 40°F and below. This report reviews existing literature and the state-of-the-art on conventional grouting engineering methods and materials to seek which may be used in thawed or dry, frozen ground and to establish the need of new methods and techniques where conventional grouting methods fail. Forty-five references are cited. ←		

PREFACE

This report was prepared by Robert Johnson, Research Civil Engineer, Foundations and Materials Research Branch, Experimental Engineering Division, U. S. Army Cold Regions Research and Engineering Laboratory (CRREL).

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This report was technically reviewed by Dr. R. Torrence Martin, Massachusetts Institute of Technology, Senior Research Associate, visiting at CRREL.

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INTRODUCTION

The recent increase in activity in the state of Alaska has focused attention on the utilization of conventional construction engineering methods in permafrost areas and in the northern states that wish to extend their construction season. Because of the short summer season the majority of all construction engineering must be carried out in frozen conditions as well as under low temperature conditions. Inexperience with such climatic conditions is producing grout setting and viscosity problems to the grouting engineers and manufacturers of grout materials or products. This leads to concern of utilizing grout for construction purposes, including structural foundations, in permafrost and/or cold environments.

This report is concerned with situations where the ambient temperatures are those encountered in cold environments, for instance, 40°F to below freezing. The soil or ground consists of material, with gradation from coarse-grained to clay, which may or may not be frozen.

The grouting problem is to increase the strength properties of soil in-situ, many feet below grade (ground level), and to make soils impermeable with a low viscosity solution which will be applicable to the soil upon being placed by pressure grouting. The grout material should result in a material with no toxic properties, and be applicable to low temperature soil adjacent to or on frozen ground, sometimes ice.

Grouting may be defined as injection of material into the pores of another material (usually soil or rock) which sets to increase strength, to decrease compressibility or decrease permeability, to consolidate, or any combination of these, of the material grouted.

There is also a method known as claquage used in the treatment of fine-grained soils in which the grout penetrates as a tongue through planes of weakness. This changes the soil by adding the effect of compacting it. Claquage also seals off volumes of soil by surrounding them with comparatively impermeable members (Leonard and Dempsey 1963). Compaction Grouting, a technique used for controlled densification of in situ soils at depth, is grouting of a viscous grout into a compactable soil mass that achieves densification by physically moving the soil particles radially from a growing "bulb" of grout, into a closer spacing. Control of the compactive effort is in the nature of the high viscosity and the high internal friction of the grouting material (Graf 1969).

This report will review existing literature and the state-of-the-art of grouting, as applied to soils, 1) to seek conventional grouting engineering methods and materials which may be utilized in thawed or dry

frozen ground as well as in low ambient temperature conditions; and 2) to establish the need of new methods and techniques where the conventional soil grouting methods fail. The major source of information was the CRREL Bibliography on Cold Regions Science and Technology, and the CRREL library. Other sources were the Smithsonian Scientific Information Exchange, National Technical Information Service, Defense Documentation Center, and the Engineering Index.

There are four basic categories of grouts that are usually referred to when grouting is favorable. They are:

- a. chemical grouts
- b. cement grouts
- c. clay grouts
- d. asphalt grouts

Each of the above categories will be reviewed in seeking materials and methods which will be applicable to low temperature environments.

PROPERTIES OF CHEMICAL GROUTS

Chemical Grout Defined

Technically all grouts are chemical grouts. However, when chemical grouts are referred to in this writing, the grout will consist of a solution of two or more chemicals which react and form a solid, semi-solid or gel. The most common in this category are sodium silicate, acrylamide, lignin, various resins, etc. The viscosity of these materials renders them favorable for grouting fine- to very fine-grain soils. Chemical grouts are listed in Appendix A.

Grout as a Trace Chemical

The use of chemical soil stabilization, as stated above, can change the basic existing soil properties and improve the existing soil chemistry that produces a new soil. Chemicals which react with the soil minerals are referred to as trace chemicals. An example is an ion-chemical such as lime which when added to sodium soil replaces the ions and produces a more stable soil. Modifications have also been produced by using trace chemicals as dispersing agents such as sodium polyphosphate and calcium lignosulfonate (Schiffman and Wilson 1958).

Referring to chemical forces, Murray (1952) indicates that the ion- or base-exchange forces, atoms, and the bonds formed chemically require considerable energy to be broken, and in the case of soil particles, a coherent mass is united by a three-dimensional network of these forces.

The forces are of two types: 1) The ionic bond that is formed by a transfer of electrons of one atom to another which forms charged particles (ions that are held together by electrostatic forces). These bonds may be affected by the solvation and ionization, depending on the surroundings in which they find themselves. Bonds of this kind may be defined as chemical or primary bonds. 2) The covalent bonds that result by the sharing of one or more electrons between two atoms are little affected by their surroundings except for forces that completely disrupt them. These bonds may be defined as physical or secondary bonds.

Generally, the physical forces are weaker than chemical forces and can be broken by physical methods such as heat or solvents, plastics being an example. Substances which are known to be held together entirely by chemical bond are crystals of diamond and salt in quartz. Two types of forces may be distinguished between the above physical forces, van der Waals and homopolar, but do nothing more than fill the voids of a soil mass. This places mechanical constraint on the movement of soil particles and alters the response of the soil mass to mechanical forces. Schiffman and Wilson (1958) tell us that the silicate and chrome-lignin grouts are used for this purpose. When the voids are filled with this type system (continuous matrix) the properties (strength, permeability) of the system are essentially those of the stabilizing agent. It is sometimes not realized that this is also the case when the soil particles are bonded to the stabilizer, because even though the soil-stabilizer bond is the first to break, the soil particles, being isolated individuals in the matrix, result in a system equivalent to the inert filler as the contributing factor (Murray 1952).

Grout as a Bonding Link

When chemicals produce adhesion or cementation by forming a bonding link, they create forces connecting the soil particles. These forces, external to the soil particles, act to hold them together, and when referring to the soil mass, these forces are internal restraints adding strength to the entire system. Calcium acrylate is a chemical of this type (Schiffman and Wilson 1958).

Chemical grouts are available in a wide range of viscosities, with some as thick as light grease, ranging down to a very thin liquid of a centipoise very near that of water (viscosity of water is one centipoise). Other than the low viscosity, chemical grout advantages are the control of setting time and the absence of the particulate material or suspended solids.

Much has been written on classification and selection of chemical grouts, and despite attempts to categorize chemical grouts, there remains overlap in areas of applications so that each case has to be individually assessed before making a suitable choice. (Plaisted 1974).

In-Place Strength and Chemical Grouting

From an extensive program directed specifically toward evaluation of chemical grouting for the purpose of increasing the in-place strength of soil, Warner (1972) reports on a testing program which has included laboratory molding of over 2,500 individual samples using eight different chemical grout systems. In addition, strength values of approximately 100 specimens from actual field applications have been correlated with the laboratory results. Basic grout types and specific systems evaluated herein are as follows: (1) Acrylamide - AM-9 10%; (2) Polyphenol Resin - Terranier 25%; (3) Resin Emulsions - (a) ALREM Soil Binder, (b) Superstruct 22-0-2; and (4) Sodium Silicate Base - (a) Earthfirm GVS 50%, (b) Modified Earthfirm 40%, 50%, and 60%, (c) SIROC - Mix samples No. 3, 7, and 13 and (d) Silicate - Bicarbonate One-Shot Method. Warner's comments are listed below (1 to 4) along with some of the figures of strength test data (Figs. 1 to 5).

1. The desirable properties of chemical grouts used for strength increase differ significantly from those used for water control purposes. Grouts used for strength increase should generally provide hard, rigid gels and long gel times. One exception would be the multiple-shot Joosten Process, where applicable.
2. The solution strength and proportions of the different components of most chemical grout systems can be varied widely. Significant changes in strength and behavior of the resulting masses occur from such variation.
3. The curing environment is the most important single consideration which influences the strength obtained from solidified mass. Significantly lower strength will occur when the mass is cured under water. Higher strengths will occur from drying. It is therefore important that test samples obtained from field applications not be allowed to dry prior to testing. In this regard, field testing and evaluation is recommended.
4. Due to its relative ease, speed, and economy, plus its providing shear values upon which most soil strength calculations depend, the unconfined compression test is the preferred method of strength determination.

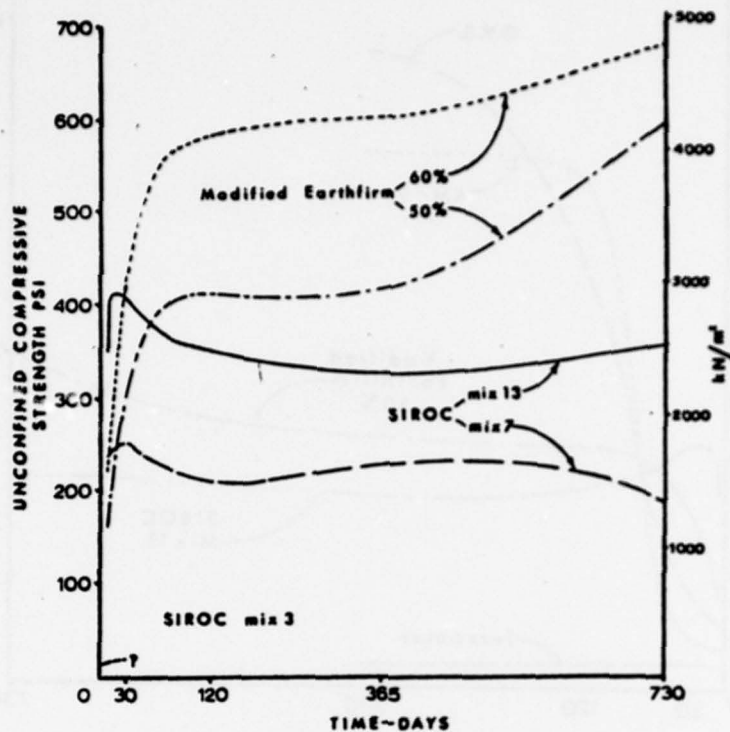


Figure 1. Strength Development of Normal Cured Specimens Prepared With Different Mix Proportions of Earthfirm and SIROC Grouts (Warner 1972). (Copyright, American Society of Civil Engineers; reprinted by permission.)

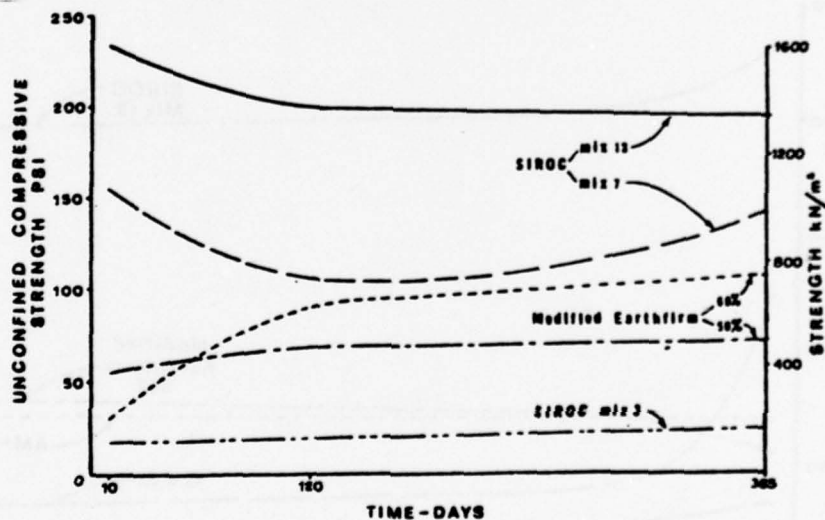


Figure 2. Strength Development of Submerged Cured Specimens Prepared with Different Mix Proportions of Earthfirm and SIROC Grouts (Warner 1972). (Copyright, American Society of Civil Engineers; reprinted by permission.)

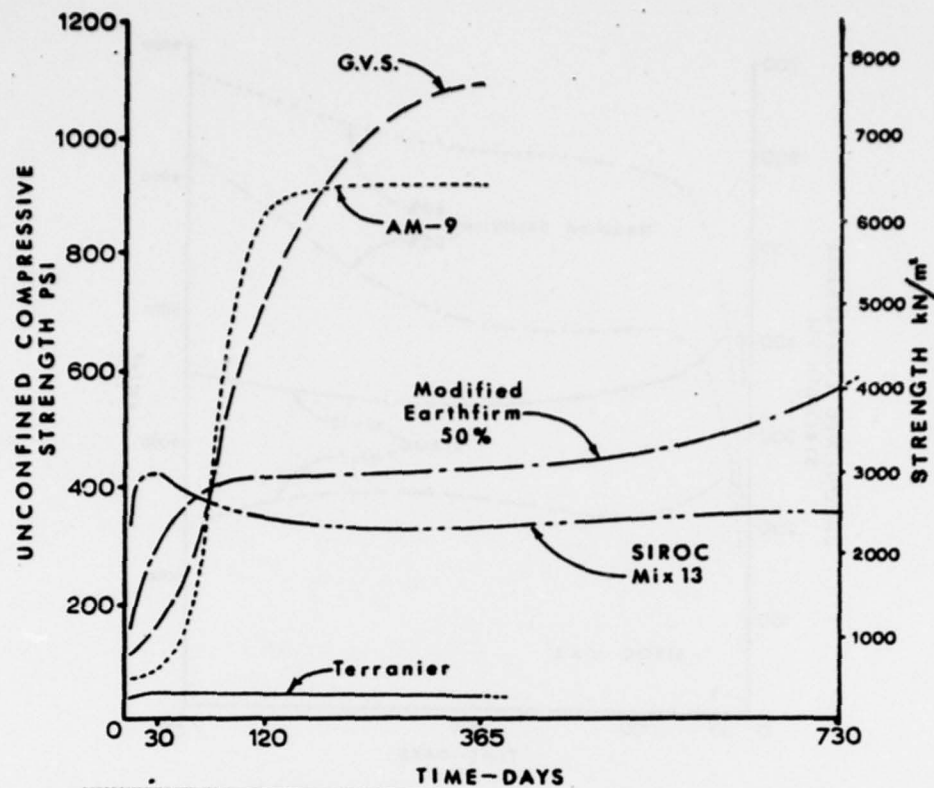


Figure 3. Strength Development of Various Normal Cured Chemically Solidified Specimens (Warner 1972). (Copyright, American Society of Civil Engineers; reprinted by permission.)

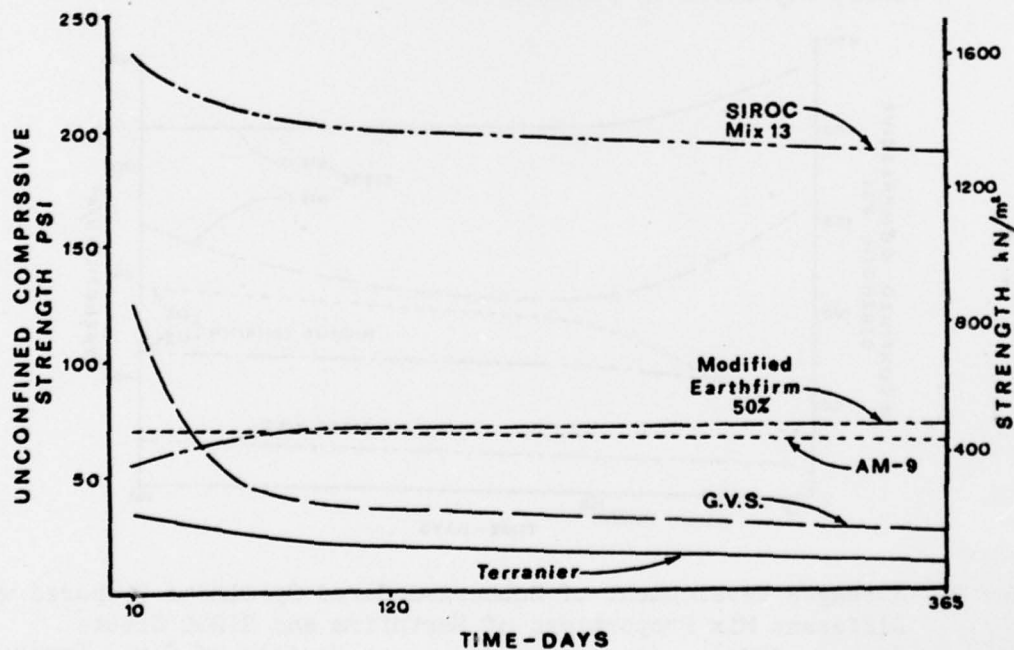


Figure 4. Strength Development of Various Submerged Cured Chemically Solidified Specimens (Warner 1972). (Copyright, American Society of Civil Engineers; reprinted by permission.)

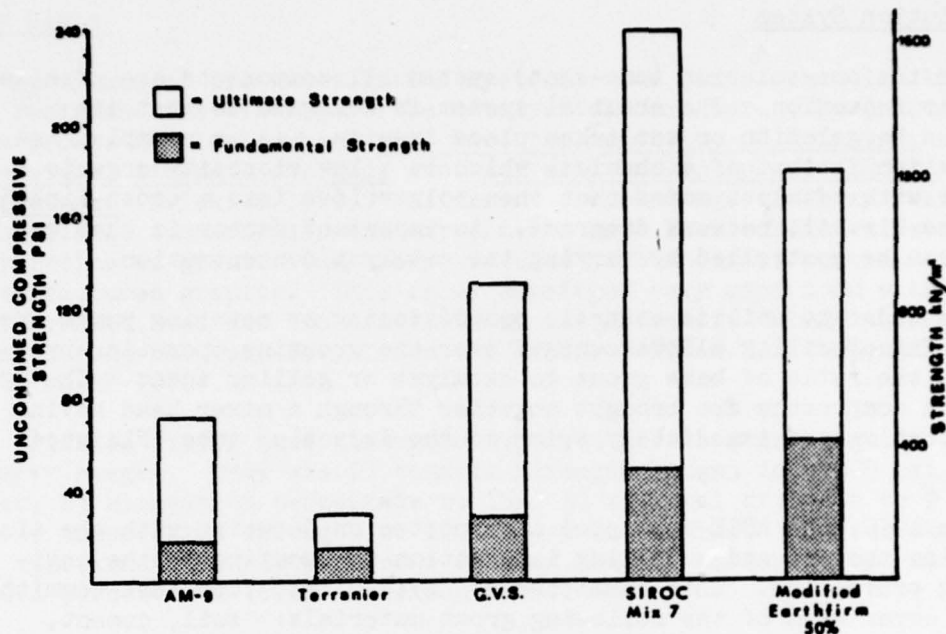


Figure 5. Ultimate and Fundamental Strengths of 5-day Normal Cured Specimens of Various Chemically Solidified Sands (Warner 1972). (Copyright, American Society of Civil Engineers; reprinted by permission.)

Note: The load which a specimen will support under a continuous stress without continued creep or rupture, defined as the fundamental strength, is significantly less than the ultimate strength of the specimen obtained from rapid loading. The fundamental strength value will vary greatly according to age, curing environment, method of loading, etc.; however, it can be as low as 20% of the ultimate strength.

Soil and Foaming Action of Polymers

In today's chemical industry special polymers have been developed to meet particular demands. However, when considering polymers for use in soils, the selection of a defoaming agent may be necessary. Fungaroli and Prager (1969) indicate that polymers tend to foam when mixed, and a defoaming agent is used to eliminate this problem; in soils this is critical because foaming action would greatly reduce compacted densities.

GROUT SYSTEMS

One Solution System

In the one-solution (one-shot) system all components are premixed prior to injection. The chemical system is designed so that its reaction to gelation or set takes place in-situ. As an example, one such system is that of a chemical which is a low viscosity organic monomer with catalyst added that then polymerizes into a cross-linked gel (See Fig. A1, network diagram). An important factor is that gel times can be controlled by varying the catalyst concentration.

In order to utilize control, proportioning or metering pumps are used. This facility allows control over the grouting operation by varying the ratio of base grout to catalyst or gelling agent. The separate components are brought together through a mixer head having non-return valves immediately prior to the injection tube (Plaisted 1974).

In 1952, the ASCE appointed a Committee on Grouting with the aim of advancing the art and supplying information on grouting to the engineering profession. This committee is divided into four task committees, one to cover each of the following grout materials: soil, cement, bitumen, and chemicals. Their report prepared by the Task Committee on Chemical Grouting summarizes the state of knowledge on this subject. The report is divided into the following main sections: Injection Processes, Injection Procedures, Summary of Field Applications, Patent Abstracts, and Annotated Bibliography (Progress Report... 1957).

Two Solution System

In the two solution (two-shot) type of process, one chemical is injected followed by the injection of a second chemical that reacts with the first to produce a precipitate in the soil void spaces and pores. The Joosten process, one of injecting sodium silicate followed by an injection of calcium chloride, results in a reaction that precipitates a silica gel that effectively fills the voids of a soil (Mitchell 1970).

Very high strengths have been claimed for the two-shot method, up to 8N/mm^2 (1160 psi) (Plaisted 1974) and 7-26 ton per sq. ft. (97-361 psi) (Hurley and Thornburn 1971). The compressive strength of sands grouted with the two-shot method is about 500 psi whereas that of sands grouted using the one-shot method is about 100 to 200 psi (Polivka and Gnaedinger 1957).

CHEMICAL GROUTS

Epoxy Resin

Epoxy resins are two-solution systems. One part is usually the base resin and the other part the catalyst or hardener. There are epoxy resin grouts available which will meet the condition of moisture, temperature, strength desired, etc. and will harden in cold (20°F) temperatures (Erickson 1968). Different compoundings of epoxy resins are available commercially and experiments have been conducted using epoxy resins as grout. One epoxy was used with moderate success to grout fractured granite. This epoxy developed very good bond with the moist granite, was not too brittle, and the effective volume shrinkage during curing was very low, Technical Manual 5-818-6/Air Force Manual 88-32 (DA/AF 1970).

Erickson states that strengths reported give a general guide for property ranges. They are 1) tensile strength ranges to 6,000 psi and higher, 2) elongation percentage to 15%, 3) flexural strength to 9,000 psi, 4) compressive strength to 10,000 psi and higher, 5) water absorption approximately 2/10th percent or less, and 6) shrinkage by volume 1/100th percent and lower (Erickson 1968).

Polyester Resin

Polyester resins are two-solution systems. They consist of the polyester resin base material and a catalyst. According to Erickson, the proportions of polyester to catalyst vary from 4-1 to 15-1 by volume and for cold temperature operations, an accelerator may be used to accelerate the setting of the system.

Erickson tells us there are polyester resins available that are formulated to be used for specific anticipated conditions, that is, temperature, moisture, etc., and that polyester resin grouts can be formulated to cure at temperatures as low as 40°F by the use of promoters (accelerators); they are capable of developing a high bond to clean, dry surfaces. Colored or fluorescent dye may be added for identifying the grout after injection. Properties of polyester grouts are 1) shrinkage during hardening can be as high as 6%; 2) time for mixing can be adjusted depending on temperature from a few minutes to several hours (Erickson 1968).

The strength, as reported in the above references, can range as high as 20,000 psi or more, with tensile strength up to 9,000 psi.

Sodium Silicate

Sodium silicate, which is alkaline, is the basic chemical used in many silicate grouts and will form a gel using an appropriate reactor. The chemical action forms a colloidal silica when the silicate solution is mixed with an acid or a salt of an acid such as ammonium salt, and the colloidal silica aggregates and forms a gel, provided the concentration of silica in the silicate solution is greater than 1-2% by volume.

Sodium silicate may be used in a single or two-solution system. Sodium silicate as a single-solution system involves injection of a sodium silicate solution including a reactant agent. The reactant agent produces the setting. The single solution permits control of radius and penetration of grout when designed as controlled gel set time (Engineering Manual EM 1110-2-3504, DA 1973).

Compressive strengths generally range from 0.5N/mm^2 (72 psi) up to 3N/mm^2 (434 psi) (Plaisted 1974). The gel strength is independent of the nature of the reactant added to promote gelation. However, the stability of the gel with the passage of time depends on the gelling agent. To obtain strong gels, one must avoid diluting the silicate, but this is not possible with the usual mineral reagents.

Sodium silicate can be used in soil stabilization mainly because it reacts with soluble calcium salts in water solutions to form insoluble gelatinous calcium silicates. However, soils or groundwater that have appreciable salt contents, even CaCO_3 , may significantly decrease the setting time for silica gels, and there is some evidence that the presence of organic matter may prevent completely the setting of some gels (Hurley and Thornburn 1971).

Commenting on a two-shot method of treatment using calcium chloride and sodium silicate (Joosten method), Plaisted (1974) tells us that the viscosity of the silicate solution may be between 80 and 180 cp, and therefore, this technique is restricted to the treatment of sandy soils having a grain size not less than 0.5 mm. Plaisted shows this in Figure 6, which also gives, including other information, aperture size in inches as related to particle size in millimeters. (Also see Fig. 7.)

Calcium Acrylate

Calcium acrylate, an organic salt, can be made by mixing calcium carbonate with acrylic acid to form calcium acrylate along with water and carbon dioxide. Grouting soils with calcium acrylate, the acrylate monomer is introduced first, and then the polymerization is

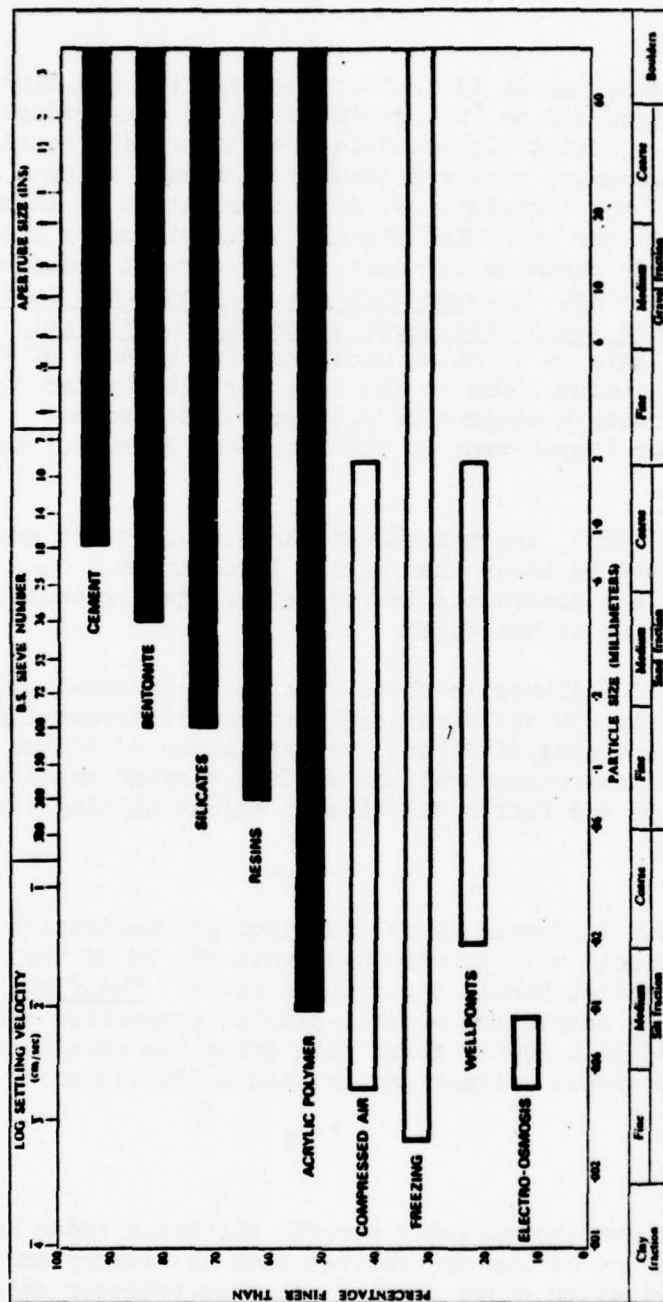


Figure 6. Limits of treatment by various methods. (Plaisted 1974.)
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produced using a redox system which consists of a catalyst (an oxidizing agent) and an activator (a reducing agent). The redox catalyst system, with ammonium presulfate as catalyst and sodium thiosulfate as activator, produces the polymerization (Lambe 1951).

Lignosulfite

Another form of chemical grout is that of lignosulfite and dichromate (chrome lignin). Lignosulfite or lignosulfonate is a byproduct of cellulose from pulp wood. Mixing lignosulfite with dichromate results in a firm gel. The gel strength varies depending upon many things. They are 1) the nature of the lignosulfite, 2) concentration of lignosulfite and chrome, and 3) the pH of the mixture. The viscosity increases in time, and the hexavalent chromium is toxic. Therefore it requires special precaution when mixing. However, this gel is not toxic in its gel form, but water leaches toxic hexavalent chromium from the gel. The toxic hazard of chrome-lignin is of vital consideration because of the toxicity of hexavalent chromium. Due to the toxicity, the United States Public Health Service permits a maximum of 0.05 ppm of hexavalent chromium in drinking water (Department of the Interior, Bureau of Reclamation 1962).

According to Caron (1963), the hexavalent chromium is toxic and, therefore, precautions must be taken when mixing lignochrome. Once this product has gelled, the dichromate is reduced by the lignosulphite to trivalent chromate, which is not toxic.

Polivka et al. (1957) indicate in their section on chrome-lignin grouting that approximately 200 different formulations of chrome-lignin grouts have been made containing different concentrations of sodium dichromate and lignin. These concentrations contain varying amounts of acids for adjusting the pH and ferric chloride to adjust setting time.

Resorcinol-Formaldehyde

This resin type grout is formed by condensation polymerization of dihydroxybenzene (resorcinol) with formaldehyde when the pH of the solution is changed (Technical Manual 5-818-6, DA 1970). The final product is a non-toxic gel possessing elastic-plastic properties and high strength when tested in a mortar form. The grout has excellent set-time control, instantaneous polymerization, and a low viscosity prior to polymerization.

Acrylamide

Chemical grouts are available, under several different trade names, which use acrylamide and one of its derivatives such as bisacrylamide which produces a polymerization cross linking gel when properly catalyzed,

trapping the added water in the gel, TM 5-818-6/AFM (DA/AF 1970). According to EM 1110-2-3504 (DA 1973), several reactants and mixtures of reactants may be used, but commonly a system of β -dimethylaminopropionitrile (DMAPN), ammonium persulfate (AP), and potassium ferricyanide (KFe) is employed. DMAPN is the activator for the reaction, KFe acts as an inhibitor and is used to control the reaction, and AP initiates the reaction. Injection is by a one-solution process with the AP solution being added to the solution containing the other chemicals, just before injection. Gel time can be controlled from a few seconds to several hours by proper proportion of all ingredients. The viscosity of the solution approaches that of water, and the solution retains its low viscosity for approximately 95% of its fluid life. The gel is stable under non-dehydrating conditions but will lose water and shrink if allowed to dry. If the gel is allowed to dry, it will, within limits, slowly swell again to its original volume upon sustained contact with water and will exhibit its original physical properties. Excessive drying will destroy the gel.

Acrylamide grouts have been used successfully in constructing grout curtains, setting off water seepage, stabilizing loose sand, shutting off water artesian flows, etc. The use of this grout has been to stop or diminish the flow of water.

Acrylamide grouts have been found to penetrate materials having a grain size of approximately 0.01 mm which is in the silt size range.

Silicate-Chloride-Amide

A silicate-chloride-amide system can be used where there is a need for an increase in the bearing capacity of the foundation material. This system has been successfully used for solidification of materials below the water table. It is a permanent grout if not allowed to dry out, and with 35% or more silicate contents by volume, the grout exhibits a high resistance to freezing and thawing (Department of the Army EM 1110-2-3504, 1973).

Silicate-Aluminate-Amide

The silicate-aluminate-amide system has been used for strength improvement and water cutoff. Its behavior is similar to the silicate-chloride-amide, but it is better for shutting off seepage or flow of water. This system can be used in acidic soils (DA, EM 1110-2-3504, 1973).

Silicate-Bicarbonate-Amide

The silicate-bicarbonate-amide system can be used for semi-permanent grouting and for various surface applications when the stabilization requirement is for relatively short periods of time (DA, EM 1110-2-3504, 1973).

Lime and Lime Grout with Silt/Clay

The word "lime", an abused term, often implies any type of calcareous material. However, according to Webster it can only refer to quicklime (calcium oxide) or hydrated lime (calcium hydroxide), which are burned forms of limestone (calcium carbonate). Lime stabilization embraces only the burned lime products -- not pulverized limestone. There are only two fundamental types of lime: high calcium and dolomitic (high magnesium). There is little (if any) difference in the effectiveness of these two types of lime for stabilization; both have been used successfully (National Lime Association 1972). Lambe (1962) has further defined the basic types of lime as follows:

High-calcium quicklime	- - - - -	CaO
Dolomitic quicklime	- - - - -	CaO+MgO
Hydrated high-calcium lime	- - - - -	Ca(OH) ₂
Normal hydrated dolomitic lime	- - - - -	Ca(OH) ₂ +MgO
Pressure-hydrated dolomitic lime	- - - - -	Ca(OH) ₂ +Mg(OH) ₂

In an article in Railway Track and Structures (1974), Dr. Heagler, School of Engineering, University of Missouri, Rolla, explained the theory of hydrated lime added to a clay soil. He stated that three possible reactions take place:

"(1) There is an ion exchange that takes place very rapidly causing changes in the attracting and repelling characteristics of the clay fraction of the soil. As a result of this reaction the physical properties of the soil change. We can expect a reduction in the plasticity of the soil, an initial reduction in the cohesion, an increase in friability and an increase in the angle of friction, and usually there will be an increase in optimum moisture content and a decrease in maximum density under standard compactive effort. According to Martin (1977) in 99% of soils this is insignificant.

"(2) The second effect is termed Pozzolanic Reaction. This reaction is associated with the development of insoluble precipitate binders derived from the reaction of calcium with the alumina or silicate

ions in the clay molecule or in the soil system. This is a long-term reaction and the cause of significant cementitious action and cohesive strength gain over a long period of time.

"(3) Finally, there is the development of calcium carbonate as a weak binder due to carbon dioxide in the soil reacting with the calcium. This is a long-term reaction and not too beneficial."

Dr. Heagler also comments, the reactions of lime with clay and silty clay soils are significant, while with sands, gravels, and the coarser soils these reactions are of minimal benefit. According to Air Force Weapons Laboratory-TR-70-84 (Robnett et al. 1971) lime has been widely used as a stabilizing agent for fine-grained plastic soils, and the most important lime-soil reaction mechanism (with respect to strength increase) is the pozzolanic reaction. The reaction involves Ca^{++} contributed by the lime and silicate and/or aluminate liberated from the soil at high pH levels. They combine to form various types of hydrated calcium silicates and/or calcium aluminates. These strong cementing products are similar to those formed in the hydration of portland cement.

Assuming that a soil is lime-reactive, a number of other factors tend to influence the magnitude of strength that is developed. The lime-pozzolanic reaction is time and temperature dependent. Below temperatures of about 40°F to 50°F, the pozzolanic reaction is retarded and may be dormant but will continue when the temperature is elevated. In some geographical locations, a low ground temperature (<50°F to 60°F) may exist in the subgrade (depths >3 to 4 ft below surface) throughout the year. In such cases, the rate of strength gain resulting from the lime-pozzolanic reaction may be quite slow. Elevated temperatures greatly accelerate the rate of reaction, although extremely high temperatures cannot be expected in the subgrade (AFWL-TR-70-84), Robnett et. al. 1972).

An increased length of curing period (at a given temperature above 40° to 50°F) produces higher strength mixtures as a result of an increased quantity of reaction product.

In general, assuming a satisfactory temperature regime exists, the pozzolanic reaction will continue as long as the lime is available to the system and the pH remains high.

In deep layer stabilization, the region of improvement that can be effected by the lime-soil pozzolanic reaction and other mechanisms is dependent on the ability to blend or permeate the soil with a lime slurry or the ability of the lime slurry to migrate away from a free source of lime such as a lime seam or a drilled hole. Due to the constraint inherent

in deep layer stabilization, lime distribution by blending or permeation processes may be limited. However, due to the nature of lime it is possible to obtain increased distribution of the lime through migration or self diffusion processes.

Diffusion of lime through the soil structure is extremely slow. Water provides a medium through which the lime can diffuse in the soil water system. Due to the interactions between the clay particles and exchangeable cations and the clay and water, the diffusion process is very complex. The intricate pore structure of an in-situ clay soil tends to retard migration in much the same way as electro-osmotic flow is resisted. Cations (such as Ca^{++}) generally migrate faster than negatively charged ions. According to Martin (1977), anions (-) generally foster the cations (+).

Indicated in the report (AFWL-TR-70-84), in a study of lime migration characteristics in large lumps of pulverized soil taken from compacted lime soil mixtures, it was found that the rate of hydrated calcitic lime penetration by diffusion into the soil system could be expressed by:

$$l = k_d \sqrt{t} \quad (1)$$

where

l = lime penetration distance, in.

t = time, days

k_d = diffusion constant, in./day

The value of k_d for the particular soil system (a plastic loess) was 0.081 in./day.

PRESSURE-INJECTED LIME

Thompson and Robnett (1976) tell us that, in an attempt to achieve better lime distribution in the soil mass, the pressure-injected lime procedure was developed. In this procedure, a lime-water slurry is pumped under pressure through hollow injection rods into the soil. Generally, the injection rods are pushed into the soil in about 12-in. (31-cm) intervals. At each depth, the lime slurry is injected to refusal. Refusal occurs when (as given by the above reference):

1. Soil will not take additional slurry

2. Slurry is running freely on the surface either around the injection pipe or out of previous injection holes, or

3. Injection has fractured or distorted the pavement surface. Although there is substantial variability in the amount of slurry that can be injected, a normal take is about 10 gal/ft (124 liters/m) of injected depth. Obviously, the nature of the soil being treated will influence the quantity of slurry that can be injected.

The normal lime-water slurry composition is 2-1/2 to 3 lb of lime/gal (0.3 to 0.4 kg of lime/liter) of water including a wetting agent added in accordance with the manufacturer's recommendation. The above slurry composition has proved to be satisfactory by experience.

Injection pressures as high as several hundred pounds per inch² can be developed with most lime slurry injection equipment, but the majority of the work is injected in the pressure range of 50 to 200 psi (345 to 1380 kPa) where the pressure is normally enough to disperse the maximum amount of slurry into the soil. Spacings of 3 to 5 ft (0.9 to 1.5 m) on centers are common in pressure injection treatment for building foundation work.

Laboratory studies have indicated that it is almost impossible to force a typical lime slurry (30 percent by weight) into fine-grained soils even when pressures of up to 1,000 psi (6.9 MPa) are applied for 20 minutes. Slurry penetrations generally averaged less than 1/2 in. (12 mm) into the silty materials, and almost no penetration was achieved in the clayey materials.

DETERIORATION OF SILICA GEL

In general, three processes may lead to the deterioration of silica gel contained in the voids of soil. These are 1) shrinkage due to spontaneous expulsion of water (syneresis), 2) shrinkage due to desiccation, and 3) solution or erosion by groundwater. All types of silica gel undergo syneresis, and laboratory tests indicate the water loss may range from 20-60% by weight, within two months. There are gels, for which shrinkage of nearly 25% of the original volume is possible depending on the type of agent and concentration of silica in the original solution. When one-shot sand-gel is subject to desiccation, it loses its cohesion and its permeability may increase almost to the original permeability of the sand. Conclusions are that gel-impregnated sand subject to a hydraulic gradient (as in a grout curtain) would deteriorate with time owing to solution or erosion by groundwater, unless other processes intervened to prevent water percolation through the ground or grouted zone (Hurley and Thornburn 1971). However, according to Plaisted (1974), its strength will increase during syneresis.

SOIL PROPERTIES RELATIONSHIPS TO GROUTS

Grout and Ranges of Soil Grain Size

Mitchell (1970, Fig. 7) indicates the use of various methods for in-place treatment of soils and uses a figure to demonstrate their use for different particle sizes and types. The figure shows, among others, three type grouting methods used for grain sizes over a range from sand to silt. Note the ranges of cement, clay, and chemical grouts.

Pore Size and Grout Material

Information from sieve analysis, bow count, water table, and holder or rock levels are often gained from soil sampling tests. The engineer must translate this information into meaningful terms of pore size and groutability ratios. According to King and Bush (1961), the key to the choice of grouting material lies in the determination of the effective pore size of the sand or gravel to be grouted. There is a relationship between the size of the grains in a system of packed rock particles and the effective pore diameter or critical ratio of entrance. They (King and Bush) show that a mathematical examination of a system of spherical particles indicates that the critical ratio of entrance or net pore diameter may vary from 15% of the diameter of the sphere at 26% void ratio to 41% at 48% voids. (See Fig. 8)

It appears to be generally agreed that no serious errors are introduced by assuming the sand grains to be spherical. Conducting tests with a neat cement grout, King comments on the successfulness of the groutability ratio being greater than 15.

$$N = 15 = \frac{D_{15}}{D_{85}} \quad (2)$$

where

D_{15} = Diameter, in microns, of effective soil grain size percent passing 15%

D_{85} = Diameter, in microns, of effective grout grain size percent passing 85%

A sand having 15% passing the number 16 sieve is said to have a D_{15} size of 1190 microns, and a cement having 85% passing the number 200 sieve has a D_{85} size of 74 microns. Therefore, the groutability ratio for the combination is $N = 1190/74 = 16$.

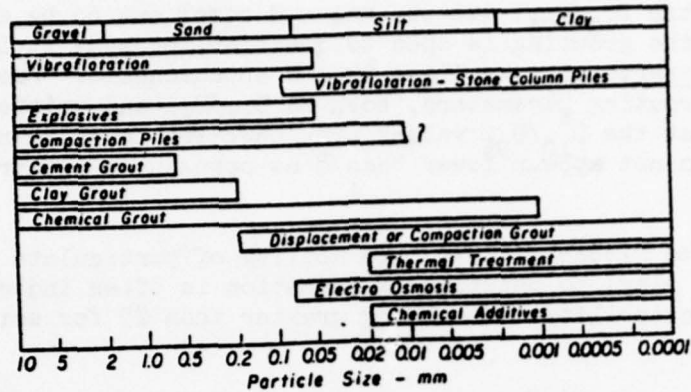


Figure 7. Particle Size Ranges for which Different Treatment Methods are Applicable (Mitchell 1970). (Copyright, American Society of Civil Engineers; reprinted by permission.)

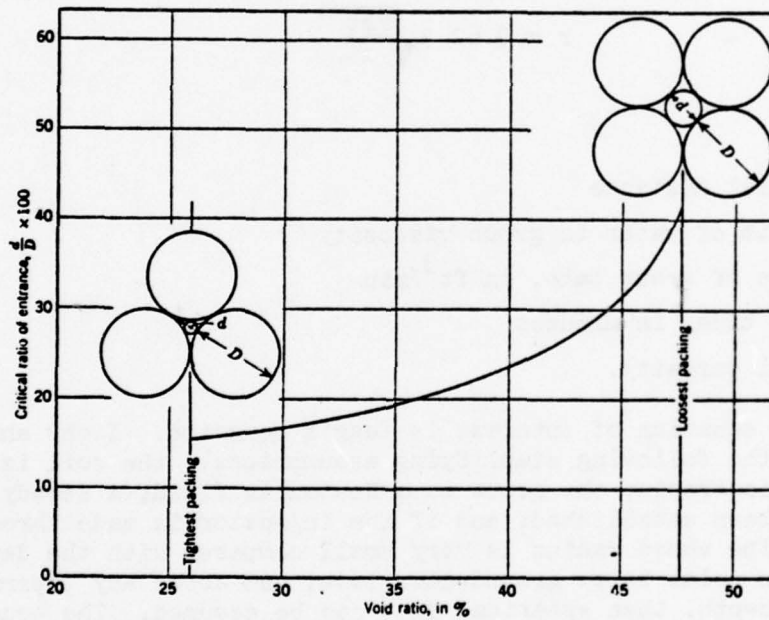


Figure 8. Systematic Packing of Spheres (King and Bush 1961). (Copyright, American Society of Civil Engineers; reprinted by permission.)

King states that it is not enough to rely solely on the D_{85} figure for the maximum size of the grouting material. The ratio $N = D_{15}^{soil}/D_{85}^{grout}$ may be satisfactory for some examples if $N = 16$; however if the N is equal to the ratio $D_{10}^{soil}/D_{95}^{grout}$, and the value N comes out to be about 8, the feasibility of the grouting is open to question, because it is known that filtering starts to take place when N approaches 6. From a number of successful grouting parameters, both as $D_{15}^{soil}/D_{85}^{grout}$ and written as $D_{10}^{soil}/D_{95}^{grout}$, it was found that the $D_{10}^{soil}/D_{95}^{grout}$ values are generally lower than the $D_{15}^{soil}/D_{85}^{grout}$ but that they do not appear lower than 8 as opposed to 6 where filtering takes place.

According to Mitchell (1970) the ability of particulate grouts (soils, cement, clay) to penetrate a formation is often indicated in terms of the groutability ratio being greater than 25 for soils

$$\frac{D_{15}^{soil}}{D_{85}^{grout}} > 25 \quad (3)$$

and that a radial distance from a grout point to which a chemical grout may be penetrated can be estimated using the equation

$$r = 0.62 \sqrt[3]{\frac{Rgt}{n}} \quad (4)$$

where

- r = radial distance
- R = ratio of water to grout viscosity
- g = rate of grout take, in ft^3/min
- t = gel time, in minutes
- n = soil porosity.

Another equation of interest is Maag's equation. Ischy and Glossop (1962) give the following simplifying assumptions: the soil is homogeneous and isotropic; the grout is a Newtonian fluid; a steady state of flow has been established; and if the injection is made through an open-ended pipe whose radius is very small compared with the depth of the injection point below groundwater level and above any impermeable boundary in depth, then spherical flow can be assumed. The equation is as follows:

$$t = \frac{an}{3khr_o} (R^3 - r_o^3) \quad (5)$$

where

- k = permeability of soil, in cm/sec
- h = injection pressure, in g/cm²
- α = ratio of viscosity of grout to that of water
- R = radius of penetration of injection, in cm
- r₀ = radius of penetration tube, in cm
- n = porosity of soil
- t = duration of injection, in sec (pumping time)

The percentages reportedly hold true when

- a. the soil is homogeneous and isotropic
- b. the grout is a Newtonian fluid
- c. spherical flow is assumed

Herndon and Lenahan (1976) state that Maag's equation is a relatively simple expression of the effects of viscosity, permeability, grouting pressure and radial distribution on grouting time, but they do not recommend its use. They indicate that one of the reasons is that it ignores resistance of water outside of the grout penetration sphere and, therefore, would probably underestimate the penetration time except in dry soil, and more importantly, it assumes that the hydraulic gradient i is constant along a radius r , which according to the equation $i = h/r$, where h is the head difference in feet of water, the grouting pressure should increase linearly with the grouting sphere radius, and this is not necessarily true. Herndon and Lenahan (1976) present a section in their work which considers this problem using Newtonian and Non-Newtonian grouts with mathematical theory. But it is beyond the scope of this report to present the above theory.

Chemical Grout Penetration of Sand

It is important that pressure-injected grouted chemicals uniformly penetrate and solidify among the soil particles. The method can be applied to sandy soils having more than $10^{-3} - 10^{-4}$ cm/s coefficient of permeability, in general. However, according to Miki (1973) when acrylamide and urea resin are grouted tightly in compacted tuffaceous sands, a part of catalyst is adsorbed upon the soil particles, and the strengthening effect may not occur at some part away from the injection pipe, and generally, the chemical penetration depends not only on the viscosity of the chemical but also on the affinity between the chemical and the soil particle.

According to Moller (1972), in recent years the emphasis on development of grout materials has tended to be towards formulating improved and cheaper one-shot grouts for the treatment of alluvials in the finer range. For grouting medium to fine sands with a permeability not less than about 10^{-5} cm/s silicate-based grouts are popular in Europe, being relatively inexpensive. Development in this respect has been towards finding new reagents. Treating fine sands and silty sands, down to perhaps 10^{-7} cm/s, the very low viscosity grouts of the resin type are used, such as those with an acrylic base and polyphenolics.

CEMENT GROUTING

According to AFWL-TR-70-84, cement pressure grouting has been used in construction since approximately 1900, and consists of a mixture of cement particles and water. Upon being mixed with water (the transporting medium) a hydration process is initiated. Type I portland cement is normally used, although Type III has been used because of its greater relative fineness.

A cement grout slurry can be pressure injected into the void spaces of rock or the pores of a soil. Due to the particulate nature of the cement grout, the minimum pore size that the grout slurry will penetrate is limited. A coefficient of hydraulic conductivity (permeability) greater than $k = 1 \times 10^{-1}$ cm/s is necessary for the penetration of cement grout. This would limit the use of cement grouting to materials more permeable than fine sand. It is stated that no amount of pressure can make a cement slurry pass through sand with grains finer than 0.59 mm. However, there is indication that by using a Type III specially scalped cement, the D_{10} of the material to be grouted can be as small as 0.29 mm.

Probably one of the most useful criteria for determining cement groutability is the groutability ratio previously given. This ratio should be greater than 20-25 for successful cement grouting (AFWL-TR-70-84, 1971). This criterion requires that the D_{15} of the soil must be larger than 1.6 - 2.0 mm since typically the D_{85} of the Type I cement is on the order of 0.08 mm. For the special Type III cement ($< 30\mu\text{m}$), the D_{15} of the soil must be larger than 0.6 - 0.75 mm (silt size).

Due to the fine-grained nature of some soils in-situ it may be virtually impossible to permeate this soil with ordinary portland type cement grouts, although in some cases fine sands and coarse silt might successfully be injected. As a result, cement grout injection into fine-grained soils probably will produce layers, seams, bulbs, spikes, etc. of grout rather than an intermixture. When this happens, strength improvement may be effected in stabilized zones; however, a degree of strength improvement will depend upon the relative strength of the grout and the relative amount of grout in the system.

The strength of the cement grout is dependent upon the grout design mix. Parameters which will influence the strength are the water/cement ratio and the amount of sand used as a filler, when necessary. The strength of sand cement grouts normally ranges from 100-700 psi, and for cement grouts containing clay filler the average grout strengths are approximately 100 psi. DA TM 5-818-6/AFM 88-32 uses a water:cement ratio of 20:1 to 0.5:1; however, it frequently uses ranges of 4:1 to 0.75:1.

CLAY GROUTS

Clay soils used as the primary grout ingredient can be divided into two classifications. One includes the natural clay soils found at or near the project site with little or no modification required, and the second includes commercially processed clay such as bentonite. Natural clay soils for use as a grout ingredient are fine-grained soils of medium to high plasticity and having a high ion exchange capacity which gives the material good thixotropic and gel properties. These soils may be used as both fillers and admixtures. The best source of soils for grouts will be alluvial, eolian, or marine deposits. Residual clays may contain excessive coarse-grained material, depending upon the nature of the parent rock and the manner of decomposition. Glacial clays are generally the least suitable because of the usually large gravel and sand content.

The properties of soils are for the most part determined by the quantity and type of clay minerals present. Common clay minerals encountered are kaolinite, montmorillonite, and illite. Kaolinite and montmorillonite are the most common and are found in various combinations in most fine-grained soils. Because of its ability to adsorb large quantities of water, a high percentage of montmorillonite is desirable for clay grouts. The clay minerals will generally make up most of the material finer than 2 micrometers (DA TM-818-6/AFM 88-32, 1970). Illite and montmorillonite are geographically more common than kaolinite (Martin 1977).

A widely used clay soil is bentonite. Because of its property of swelling in water, of giving thixotropic suspensions at low concentrations, it is useful for its impermeability to water flow. Conducting experiments on the flow of bentonite grouts through glass capillaries, Marsland and Loudon (1963) concluded, in part: "1) Bentonite grouts up to a concentration of 8 percent by weight (distilled water) behave only approximately as Binghamian bodies and the apparent viscosity and yield strength increase very rapidly with the concentration of grout. 2) For the particular grouts studied, a capillary model provides a means of relating the flow characteristics of grouts in sands to the flow characteristics determined in capillary tubes. This means that the flow

properties of a grout in any sand can be assessed from measurements made in a capillary viscometer, provided the water permeability of the sand is known. 3) The pressure gradient necessary to push the grout out of either a capillary tube or a sand bed after resting overnight was appreciably lower than the normally-defined yield gradient.

"Clay suspensions by themselves are usually slightly alkaline and will tend to flocculate on the addition of acidic materials. The pH value of the final grout suspension should be in excess of 7, the neutral point on the pH scale; if not, it should be adjusted by the addition of dispersants, such as the sodium phosphates." (Leonard and Dempsey 1963) However, this should not be added if you want the clay to gel (Martin 1977).

CEMENT-BENTONITE GROUTS

Cements can be used in clay grouts to produce a set and/or to increase the grout strength. Jones (1963) comments on a) cement-bentonite suspensions, b) the conversion of the bentonite to its calcium-exchanged form, and c) limitations on the quantity of bentonite which can be incorporated in a mix. The comments are as follows:

"Addition of bentonite to water-cement slurries greatly extends the range over which suspensions free from segregation by settlement may be obtained. The dry bentonite and cement powders may be mixed together and subsequently added to water, or a pre-gel of bentonite may be made and added to the cement slurry.

"Conversion of the bentonite to its calcium-exchanged form undoubtedly occurs, through reaction with free lime derived from the cement. The calcium bentonite is then flocculated by the excess of cations (mainly calcium) present in solution in the continuous phase. The flocs so formed are still gelatinous and prevent sedimentation of the relatively coarse cement particles. The primary role of the bentonite thus appears to be that of a suspending agent.

"In general, limitations on the quantity of bentonite which can be incorporated in a mix are imposed by the following factors:

(1) Workability of the mix: increasing the concentration of bentonite leads to an increasing stiffness in the slurry, eventually making it unpumpable;

(2) Final compression strength: substantial additions of bentonite to cement slurry decrease the compressive strength of the set cement;

(3) Grout specific gravity: low specific gravity grouts showing a reduced tendency to migrate through the soil after placement are obtained by increasing the bentonite concentration in the mix;

(4) Stability towards sedimentation: the concentration of bentonite in the mix must be increased as its cement content is lowered if slurries resistant to settlement are to be obtained."

Clay-cement, Carongel (silica gel) and phenoplastic resins have been used on the various size sands and Table I shows a classification for these and other grouting materials (Janin and Le Sciellour 1970). Note the permeability, grain diameter, and series of grout mix as related to the type of impermeability grout.

Type of soils		Coarse Sands and Gravels	Medium to fine Sands	Silty or Clayey Sands, Silts
Soils Characteristics	Grain diameter	$d_{10} > 0.5 \text{ mm}$	$0.02 < d_{10} < 0.5 \text{ mm}$	$d_{10} < 0.02 \text{ mm}$
	Specific Surface	$S < 100 \text{ cm}^{-1}$	$100 \text{ cm}^{-1} < S < 1000 \text{ cm}^{-1}$	$S > 1000 \text{ cm}^{-1}$
	Permeability	$K > 10^{-3} \text{ m/s}$	$10^{-3} > K > 10^{-5} \text{ m/s}$	$K < 10^{-5} \text{ m/s}$
Series of Mix		Bingham Suspensions	Colloid Solutions (Gels)	Pure Solutions (Resins)
Consolidation Grouting		Cement ($K > 10^{-2} \text{ m/s}$) Aerated Mix	Hard Silica Gels: - double shot: Joosten (for $K > 10^{-4} \text{ m/s}$) - single shot: Carongel Glyoxal Siroc	Aminoplastic Phenoplastic
Impermeability Grouting		Aerated Mix Bentonite Gel Clay Gel Clay/ Cement	Bentonite Gel Lignochromate Light Carongel Soft Silicagel Vulcanizable Oils Others (Tarranier)	Acrylamide Aminoplastic Phenoplastic

Table I. Limits of Grouting Ability of Some Mixes (Janin and Le Sciellour 1970). (Copyright, American Society of Civil Engineers; reprinted by permission.)

ASPHALT GROUTS

Large surface flows of water can be difficult to stop by grouting with cement, soil, or chemical grouts. For these conditions asphalt grouting has occasionally been used successfully, particularly in sealing watercourses in underground rock channels. It has also been used to plug leaks in cofferdams as well as in natural rock foundations. Asphalt is a brown-to-black bituminous substance that belongs to a group of solid or semisolid hydrocarbons. It occurs naturally or is obtained as a comparatively nonvolatile residue from the refining of some petroleum. It melts between 150° and 200°F. When used for grouting it is generally heated to 400° or 450°F before injection.

Asphalt emulsions have also been used for grouting. These are applied cold. In the emulsion the asphalt is dispersed in colloidal form in water. After injection the emulsion must be broken so that the asphalt can coagulate to form an effective grout. Special chemicals are injected with the emulsion for this purpose. Coal-tar pitch is not a desirable material for grouting since it melts more slowly and chills more quickly than asphalt grout. When heated above its melting point, coal-tar pitch also emits fumes that are dangerous to personnel (DA TM 5-818-6/AFM 88-32, 1970).

HISTORICAL NOTE ON GROUTING OR INJECTION PROCEDURES

The term grouting has come to replace the older term injection process. This process is one in which a material (usually liquid or liquid slurry) is forced under pressure into void spaces of soil, fissured rock, or into cavities of faulty masonry, etc. This material is usually one that, with the passage of time, will solidify by chemical or physical action (Ischy and Glossop 1962). This material, referred to in this report as grout, is forced into the soil through pipes which have been strategically placed to limit the zone of soil to be treated.

Pressure grouting, as reported in the above references, was invented and first applied in 1802 by a French engineer, Charles Berigny, who named it the injection process and used slurries of clay or of hydraulic lime. To inject them he invented a percussion drum of which the piston was driven down by a mallet. This process was much used in France during the first half of the 19th century, mainly for the repair of sub-aqueous foundations. Introduced to England in 1856 by W. R. Kinipple, the inventor of the grouted concrete, it was last used on the Delta Barrage in Egypt in 1891.

In 1876 Thomas Hawksley injected portland cement grout by using a gravity head. This was done to seal fissured rock beneath the

foundation of a dam at Tunstall. In 1886, Greathead invented the compressed air grout pan to fill the space between the lining and the ground in shield-driven tunnels. This device found other applications in engineering practice. Between 1880 and 1905 a group of mining engineers, notably Reumanux, Portier, Saclier, and Francois, working in the coal fields of northern France and Belgium, introduced injections of portland cement grout as an aid to shaft sinking in fissured and water bearing rock. They developed high pressure grout pumps and invented a number of improvements and the mixing and injection of grout, which were soon applied in tunneling and in the treatment of dam foundations (historical note from Ischy and Glossop 1962).

GROUT RHEOLOGY

Winterkorn and Fang (1975) indicate that the injection process comprises two main sections: "the knowledge about the grouts in which the chemical compositions are secondary to those of rheological behavior, i.e., viscosity, rigidity, granular state, and the technique of injecting the grout into the soil. The finer the soil to be injected, the more liquid the grout has to be ; e.g.: Binghamian suspensions (on the basis of cement or clay) in coarse soils; colloidal solutions more or less viscous (silicate or lignochrom gel, bitumen emulsion, organic colloids) in soils with medium grain size; and pure solutions (organic monomers in watery solution) in very fine soils."

Under these conditions the fundamental difference between the grouts is of rheological origin, and the following classifications can be made: a) nongranular Newtonian grout and b) granular Binghamian grout. Their comments on each are as follows:

"Nongranular Newtonian Grout - The most simple grout corresponds to a liquid without rigidity, whose viscosity - independent of the speed gradient - is invariable with time.

"Such types of grout have only been known for some years. They are prepared with organic monomers (acrylamide, phenoplast, aminoplast) diluted in water.

"The viscosity of the noncolloidal mixtures does not vary before mass polymerization takes place. The discharges are, therefore, at any moment, directly proportional to the pressure and do not depend on the age of the grout. As the viscosity of these grouts is similar to that of water, the grouts can be used in very fine soils (silt, clayey sand, etc.). Chemically they belong to three different classes:

"1. The acrylamide modified by reticulation. After polymerization this resin is very elastic but has little strength even at high concentrations. Therefore, the acrylamides are generally used for impermeabilization work rather than for consolidation (increase in strength and bearing power).

"2. The urea-formols (formaldehydes). This resin can be used for both impermeabilization and consolidation. As its polymerization takes place only in an acid medium, it is incompatible with calcareous soil. In this case one may carry out a pre-injection of acid which destroys the carbonate, but the void index as well as the expense is also increased.

"3. The resorcinol-formols are also convenient for impermeabilization and consolidation. As the catalyst takes place in a basic medium, the compatibility is perfect in any soil. At present this constitutes the most reliable method."

It is not always necessary to use a highly liquid grout. Occasionally, such as for fine or medium sands, the grouting can be accomplished with a viscous non-granular grout. Silica gel is a type of grout used. According to the above reference, depending on the concentration of sodium silicate the initial viscosity can vary between 4 and 20 centipoises. These mixtures are purely Newtonian before gelification and have a viscosity which increases with time. Upon setting they appear rigid with simultaneous transformation of the Newtonian liquid into a Binghamian liquid.

"As these mixtures have no rigidity, there is a linear relationship between discharge and pressure. However, as the viscosity increases with time, a decrease in discharge can be observed at constant pressure. This decrease, reproduced in units of permeability k , leads to the curves of [Figure 9], obtained with gels of variable setting time. If, on the other hand, a constant discharge is required, the grouting pressure has to be increased [Fig. 10]" (Winterkorn and Fang 1975).

The simplest grout corresponding to these characteristics is the silica gel, which can be used both for impermeabilization and consolidation.

For the purpose of impermeabilization, a very diluted silicate may be used (such as one part of silicate to nine parts of water). The addition of an acid or a polyvalent salt slowly transforms this solution slowly into a gel. For the purpose of consolidation, a more concentrated silicate solution (such as seven parts of silicate to three parts of water) is used. The reaction of transformation into a gel must take place in the ground. Therefore, the silicate and the gel forming agent

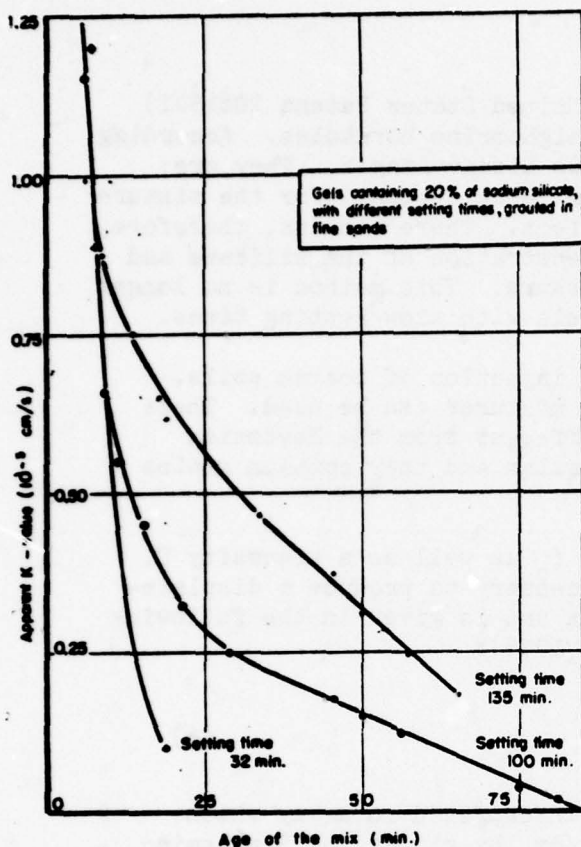


Figure 9. Variation of the Coefficient of Apparent Permeability of the Gel During Setting (Winterkorn and Fang 1975). (Copyright, Van Nostrand Reinhold Company; reprinted by permission.)

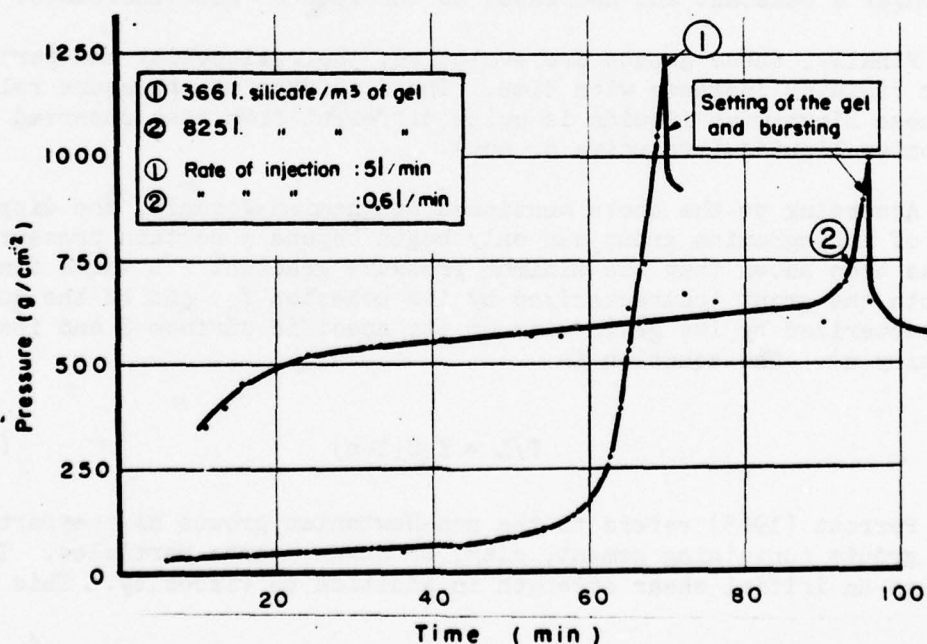


Figure 10. Evolution of Injection Pressure of Gels at Constant Rate of Discharge (Winterkorn and Fang 1975). (Copyright, Van Nostrand Reinhold Company; reprinted by permission.)

(calcium chloride in the Joosten method, United States Patent 2081541) are separately brought down through two neighboring boreholes. According to the above reference, this method has two disadvantages. They are: 1) the output of the operation is far from being optimal, for the mixture of the silica and its agent cannot be perfect. There remains, therefore, silicate which has not set; 2) the interpenetration of the silicate and its agent requires very high grouting pressure. This method is no longer in use, as it is now possible to obtain gels with slow setting times.

Granular Binghamian Grouts - For the injection of coarse soils, grout slurries of cement or clay or their mixtures can be used. These grouts are not Newtonian, and they are different from the Newtonian products for two reasons. They are Binghamian and they contain grains or particles.

A Binghamian grout offers a rigidity f_0 as well as a viscosity U , simultaneously. The effort F that is necessary to produce a displacement corresponds to a speed gradient dv/dx and is given in the following equation (comments of Winterkorn and Fang 1975):

$$F = f_0 + U \frac{dv}{dx} \quad (6)$$

This Binghamian relationship can also be interpreted in a way which approaches the law of Poisseuille, $F=U'dv/dx$, by giving the Binghamian liquid a simple term of viscosity. In this case, the viscosity term is no longer a constant and decreases as the rate of flow increases.

Finally, these grouts are evolutive; their viscosity and particularly their rigidity increase with time. The discharge vs. pressure relation of these Binghamian liquids is quite different from that observed for Newtonian liquids (evolutive or not).

According to the above mentioned Binghamian formula, the displacement of a Binghamian grout can only begin beyond a certain pressure. It has been shown that the minimum pressure gradient P/L was a function of both the grout (characterized by its cohesion f_0) and of the soil (characterized by its grain size or its specific surface S and its porosity n). The equation is

$$P/L = f_0 S(1-n) \quad (7)$$

Perrott (1965) refers to the non-Newtonian grouts as the particulate grouts containing cement, clay, or other coarse particles. These possess an initial shear strength in addition to viscosity. This initial

shear strength or yield value must be overcome before the grout begins to flow; thus an additional driving force is required. For the Newtonian grouts, most chemical grouts belong to this group, although in certain circumstances the formation of silicate gels in grouts based on sodium silicate can occur in such a manner that the grout becomes particulate.

Most natural soil deposits will be stratified, and such deposits will have a greater permeability in the horizontal direction than they have vertically. Even a single stratum of soil often exhibits this characteristic. Thus, the idealized shapes that can be obtained by laboratory experimentation under uniform conditions cannot often be obtained in field work.

In-situ, the grout injected first should flow into the more permeable zones. When these start gelling, the grout currently being pumped should be forced into the less permeable strata. This procedure will be accompanied by an increase in pumping pressure as the coarser strata are sealed off. These higher pressures, together with the limited soil cover, available in laboratory scale tests, have limited the extent to which this procedure can be verified experimentally (Karol and Swift 1961).

FLUID RESISTANCE AND FLOW

Liquid Viscosity

The viscosity of a liquid is the property which is responsible for the internal resistance offered to the relative motion of different parts of the liquid. Such internal resistance or friction, involved in the motion of one layer of molecules with respect to the next, is closely connected with the interactions (van der Waals forces, dipole interactions etc.) between separate molecules of the liquid and with the structure of the liquid phase. A quantitative description of the viscosity of a pure liquid in terms of the properties of a single molecule is therefore dependent upon our knowledge of the liquid state which, for good reason, has lagged considerably behind that of the solid and gaseous phases (Alexander and Johnson 1950).

The coefficient of viscosity is a term used to denote the frictional resistance of a fluid and is defined in terms of the tangential forces F , between two layers dx apart, moving with a relative velocity dv , with

$$F = nA \frac{dv}{dx} \quad (8)$$

where

n = coefficient of viscosity

A = area of surface undergoing relative motion

It is assumed that the motion is non-turbulent (stream-line).

In the c.g.s. system, the unit of viscosity is the poise which has the dimensions dyne-sec/cm². A viscosity coefficient of 1 poise will require a force of 1 dyne to maintain a flow of 1 cm/sec between fluid layers of 1 cm² cross-section at a distance of 1 cm apart. The reciprocal of the viscosity is termed the fluidity of a substance.

The ratio of viscosity/density of a substance is known as the kinematic viscosity and has the dimension cm²sec⁻¹. The unit of kinematic viscosity is known as the stoke.

Specific viscosity. If η_s = viscosity of solution of concentration C in g/100 ml, η_o = viscosity of pure solvent

$$\frac{\eta_s - \eta_o}{\eta_o} = \eta_{sp} = \text{specific viscosity of solution.} \quad (9)$$

Intrinsic viscosity. η_{sp}/C varies approximately linearly with C and its value when extrapolated to zero concentration is known as the intrinsic viscosity η_{int} , Encyclopaedic Dictionary of Physics (Thewlis 1962).

Grout Viscosity

Two properties of the solutions which materially affect grout injection are initial viscosity and the viscosity-time curve of the reacted grout. Initial viscosities of chemical grouts vary from 1.2 centipoises (cp) (water is 1 cp) for monomers to as high as 60 cp for asphalt emulsions. It is obvious that a grout solution with the consistency of water would be easier to inject than one which had the consistency of molasses. The other factor mentioned was the viscosity-time curve. Some grout solutions, after they are mixed, remain at a near constant viscosity until just prior to solidification at which time the viscosity rises rapidly, while other grout solutions continue to increase in viscosity from mixing time until solidification occurs. This later condition, of course, limits injection times as well as rates (Graham 1964).

Where the grout solution must penetrate the pores of a soil mass, the viscosity becomes an important parameter. The lower viscosity grouts will penetrate five soils more effectively than higher viscosity grouts. However, viscosity of various grouts may be regulated by the percent concentration of chemical. Reference EM 1110-2-3504 (DA 1973) shows a figure that compares various grout viscosities to the percent concentration of chemical (Fig. 11). Also, to be considered with some grouts, viscosity increases during gel formation and should be noted where gel times are not controlled.

There may be other potential problems related to the viscosity of the grout. According to Amaral and Frobenius (1974), in construction of the Sao Paulo subway (tunnel), sands and silts were not permeated, but split, by sheets of bentonite cement, which has a relatively high viscosity. The injected bentonite cement grout consolidated the soil under the applied grouting pressure, and caused uplift of adjacent buildings.

GEL TIME VERSUS TEMPERATURE

Gel time versus temperature conditions vary among various grouts. Many grout gel times decrease (less time) with rise in temperature. From reference EM-1110-2-3504 (DA 1973) two figures show this relationship, Fig. 12 for acrylamide grout and Fig. 13 for lignosulfonate.

INJECTING GROUTS

Physics of Injection

In grouting a soil mass, pipes or boreholes are driven into the mass in a regular pattern, and then the grout is injected. These injection points must be spaced so that the whole mass can be saturated, so far as it is necessary, from a minimum number of points. This raises certain theoretical considerations.

According to Ischy and Glossop (1962), the simplest case, that of the injection of a Newtonian liquid through an open end pipe into a uniform mass of sand and assuming spherical potential, it can be shown by using Maag's equation (previously given) that R , the maximum radius of the injection zone after a period of injection time, t , is proportional to the cube root of 4 variables. These are the permeability of the soil k , the injection pressure h , the period of injection t , and the viscosity of the grout V .

Evidently, it is desirable that R should be as large as possible for the cost of the whole operation is largely dependent on the number of spacings ($<2R$) of the injection which must, in many cases, be installed in lined boreholes, and consequently expensive. This can only

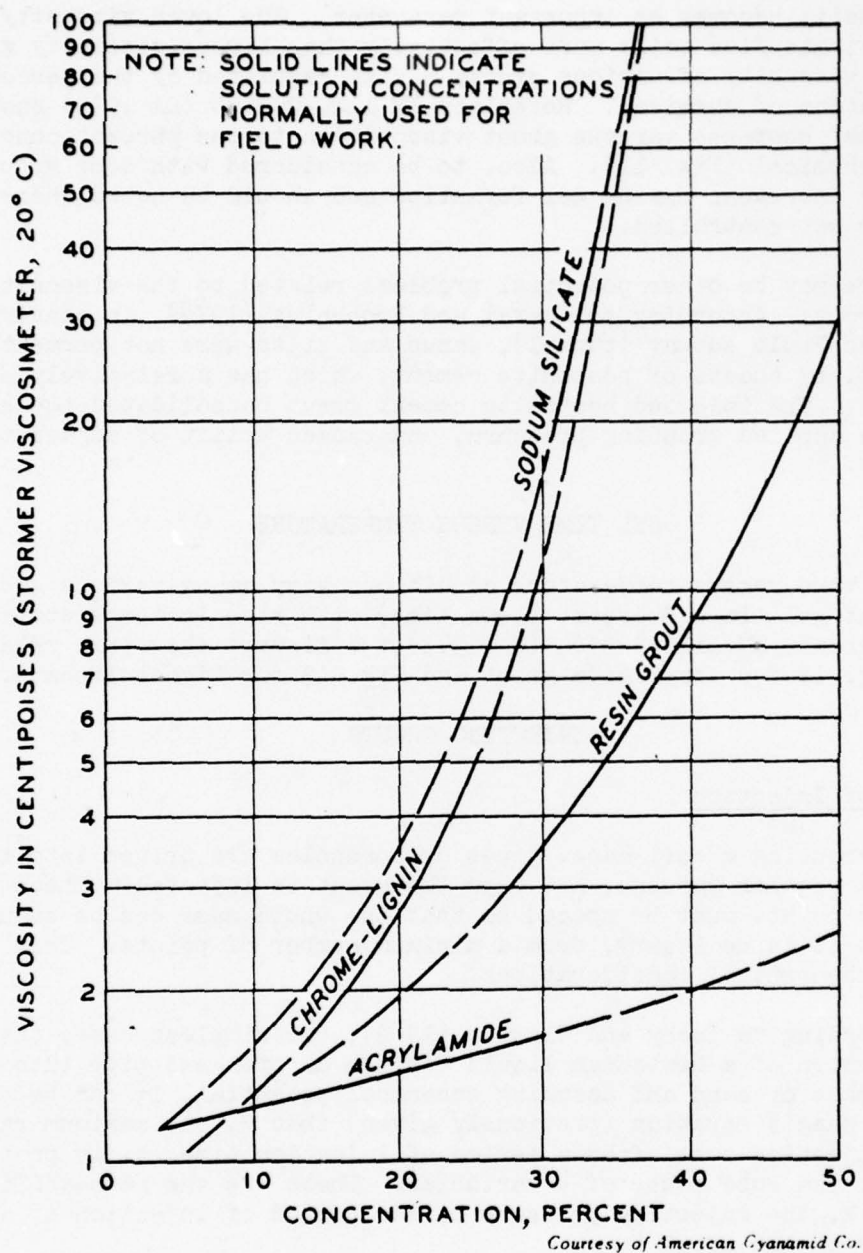
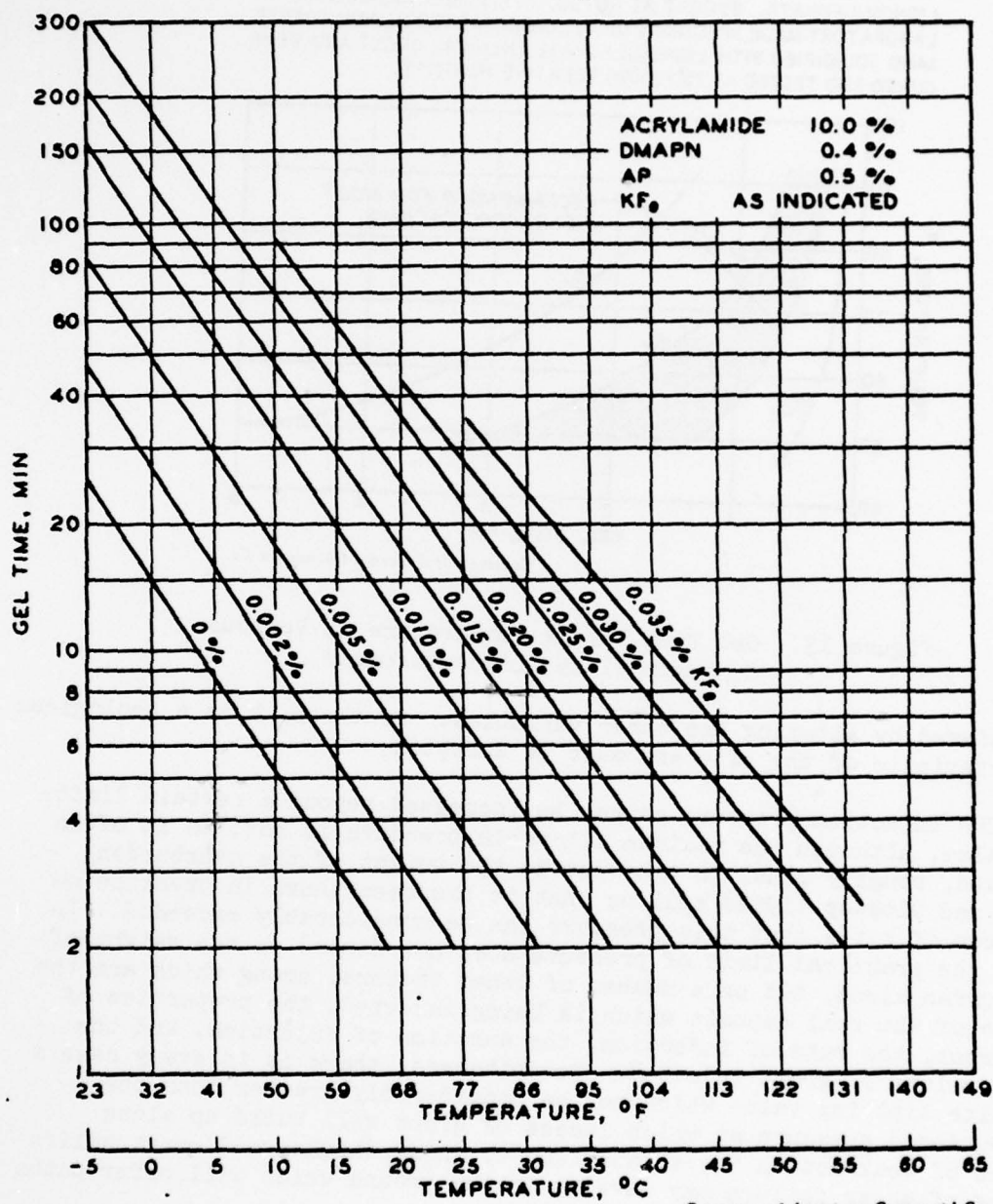


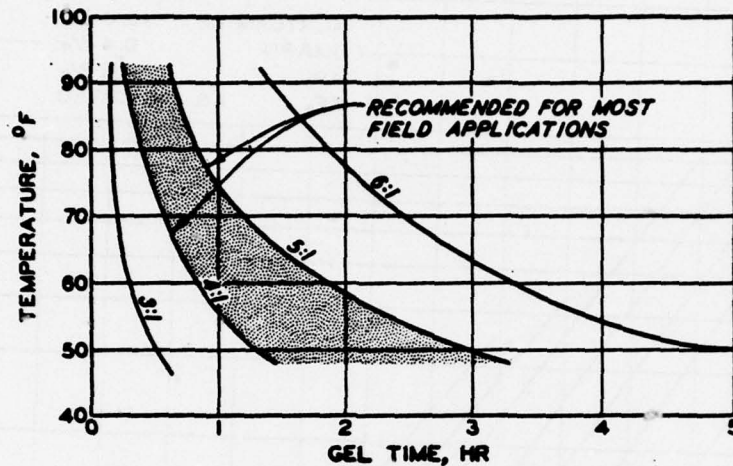
Figure 11. Viscosities of Various Grouts--Heavy Lines Indicate Solution Concentrations Normally Used for Field Work



Courtesy of American Cyanamid Co.

Figure 12. Gel Time Versus Temperature, Acrylamide

ALL MIX PROPORTIONS DESCRIBE THE WEIGHT RATIO OF WATER TO LIGNOSULFONATE. EXCEPT AS NOTED, TESTS WERE CONDUCTED ON LABORATORY-MADE SPECIMENS OF WELL-COMPACTED MEDIUM COARSE SAND SOLIDIFIED WITH LIGNOSULFONATE CHEMICAL GROUT AND WERE CURED AND TESTED AT 70° F, 100% RELATIVE HUMIDITY.



Courtesy of Concrete Chemicals Co.

Figure 13. Gel Time Versus Temperature at Various Concentrations, Lignosulfonate.

be achieved by altering the other variables. Of these, k is a geological characteristic of the site and must be accepted.

The injection pressure cannot be increased beyond a certain limiting value, although the maximum allowable pressure is not, as is often supposed, roughly equal to that due to the weight of the overburden. Ischy and Glossop (1962) tell us that it has been shown in practice on a number of sites that this pressure can be considerably exceeded. In fact, the practical limit of pressure does not depend on the weight of overburden alone, but on a number of other factors, among which are the nature of the soil deposit which is being injected, the properties of the grout, the rate of injection, the duration of injection, and the total volume of grout injected. Nevertheless, there is in every case a definite limiting value which may be considerably greater than the overburdened pressure at which lenses of grout will build up along planes of weakness in the strata, and as these thicken and exert uplift planes of shear failure may develop in the ground which will offer paths of escape to the surface.

On the grounds of cost alone the time of injection at any point must be confined to a few hours at the most and is, in any case, limited by the setting time of the grout; as a rule, slow setting grouts are weak. It follows that generally, R can only be increased by the use of low viscosity grouts, and this is particularly desirable where the value of k is low.

The Maags formula, although useful in demonstrating the principles of injection, is based on a number of simplifying assumptions and can only be very rarely used quantitatively as a guide to work in the field. In practice it is usual to make a certain number of laboratory tests on the soils to be treated, but since the samples used will be disturbed and their structure destroyed, it is preferable for large grouting projects to carry out field trials on the site.

In fact, the procedure of a normal soil mass grouting operation is as follows: a grout of comparatively high viscosity and high gel strength is first injected to fill the more permeable channels in the deposit. This injection is carried out under a pressure which will depend on the structure of the soil, on the viscosity of the grout, and on the depth at which the treatment is applied. It will generally be limited to a maximum value above which the grout pressure in the coarse strata will compress the finer soils between them, until they develop fissures through which the grout may escape, to waste, either in permeable beds outside the zone to be treated, or even to the surface.

Fissure formation under pressure, though generally undesirable, is sometimes provoked deliberately. For example, in forming an impermeable grout curtain in a soil profile which includes lenses of silt, high pressures may be used to create a network of grout-filled fissures, in which the silts (which cannot be penetrated) are not only compressed and rendered still more impermeable, but are encapsulated and protected against internal erosion.

Following the first series of viscous grouts, successful injections are made using grout of lower viscosity and greater penetration power, to impregnate the finer-grained and less permeable beds. In this way the degree of saturation of the soil can be gradually increased so far as is necessary to achieve the purpose of the operation with economy. Thus, where it is wished to reduce the flow of water through a soil deposit, it may suffice to seal the more permeable beds only, but where the grouted zone is to become part of a permanent structure, and strength is required as well as low permeability, then the ground should be saturated as completely as possible.

In practice, complete saturation of the soil is never obtained, except perhaps with a sand of almost uniform grain size. Taking into account the loss of excess water from certain grouts under the pressure of injection, experience has shown that under normal conditions an alluvial material will have been satisfactorily treated when the volume of grout injected is equal to about 50% of the volume of the voids in the soil. As grouts are now available which will seal and strengthen the soil mass of different structures and over a wide range of grain sizes, the process can be applied to almost any engineering problem to which grouting gives the most economical solution. The choice of grouting materials in any particular case depends upon the basic grout properties listed below:

1. Stability - A grout must remain stable during the processes of mixing and injection; that is to say, if it is in suspension there must be no permanent sedimentation and, if a liquid, no premature set.
2. Particle size - In a suspension, the particle size sets a lower limit to the grain size of the soil which it can penetrate.
3. Viscosity - The viscosity is a measure of the degree to which the grout can penetrate fine soils. The other flow properties and the gelling time determine the maximum value of the radius of injection.
4. Strength - This is the strength when set. The importance of this depends on whether strengthening or sealing of the soil is required; it should in any case be high enough to resist any tendency to creep.
5. Permanence - The grout when set must resist chemical attack and erosion by groundwater.

The Injection Method

According to Esrig (1968), as the soil becomes finer grained, the particle size of the grout and its viscosity must decrease if successful injection is to be achieved. Normally pressure grouting is feasible for materials with hydraulic permeabilities in excess of about 5×10^{-4} cm per second.

Different injection methods have been developed. However, if a single phase injection is sufficient, there are two processes where drilling and injection are combined (Winterkorn and Fang 1975).

- 1) A very pervious soil may be injected during rotary drilling. During the drilling of the borehole, each time a predetermined distance

has been reached the drill rod is withdrawn to a certain length and the grout is injected through the drill rod into the soil. During each injection the top of the grout hole is sealed by a column.

Another process more frequently employed for single phase injection is to drive a casing in to full depth, withdraw the casing a predetermined length, and inject through it. This method is effective only if the grout does not remount outside the casing.

2) The sealed-in sleeve pipe injection is a multiple phase process which allows several successive injections in the same zone. This involves placing a sleeve pipe into a grout hole, which is kept open by casing or by mud. This pipe is permanently sealed and with a sleeve grout composed of a clay cement mixture the sleeve grout seals the borehole between the pipe and the soil to prevent the injection grout from channeling the borehole. This means that under pressure the injection grout will break through in the radial direction and penetrate into the soil. The sleeve pipe consists of a steel or plastic tubing with a diameter of 1 to 2 inches. Plastic tubes are used to facilitate excavation work afterwards.

At 1 ft intervals, small holes have been drilled in the pipe to serve as outlets for the grout. The holes are tightly covered by rubber sleeves (manchettes) which open only under pressure. The holes and sleeves work as one-way valves.

The sleeve pipes are used only in the grouting zone whereas regular pipes are used for the rest of the grout hole.

In order to inject through a sleeve, a double packer filled at the end of a smaller diameter injection pipe is inserted into the sleeve pipe and centered around the sleeve to form a closed chamber with one-way valve outlets.

This method presents numerous advantages. First, there is the possibility of repeating injections several times, which permits the use of grouts with decreasing viscosity. This permits better penetration of the fine voids after the big ones have been closed. More pervious soil layers may be sealed first, regardless of the order of injection level, which prevent loss of high cost, low viscosity grouts. Also, the grouting operations are carried out completely independent of drilling and are very convenient for job organization and the use of grouting plan.

A Note on Injection Pressures

Discussion of injection pressure usually leads to divided opinions because theoretical considerations do not always agree with practical experience.

The pressure which is measured at the entry of a grout hole is always higher than the overburdened stress at the level of injection. Otherwise, it would not be possible to inject a soil, say, 5 m underneath ground surface with 5 kg/cm² pressure without encountering considerable uplifts (Winterkorn and Fang 1975).

A Note on Saturated Soil Injection and Silicate Grout

Saturated soils are difficult to stabilize because of the excess water filling their pores. When a water-glass grout is injected, the water present in the soil pores hinders the spreading of the sodium silicate and reduces its concentration; as a result, the obtained strength of the soil mass is low, and the stabilization radius and volume are small. If by any method the water in the pores is removed or expelled and a silicate grout is injected in the free space, this may lead to increase in the strength of the soil and in the radius of the stabilized mass (Zelenski and Isaev 1975).

GROUT COST

Air Force Weapons Laboratory report AFWL-TR-71-90 (Robnett et al. 1972) describes a study conducted to examine existing soil stabilization techniques, procedures, and technology to increase the strength of soil materials beneath existing airfield pavements. Published in this report is a table which summarizes characteristics of various stabilization procedures. Note: this table relates cost to grout stabilization procedure as well as other information. See Table II.

Badappanavar (1974) tells us that even though the cost of chemical grout is more than that of the suspended grouts, owing to the possibility of using chemicals at a lower concentration and with a minimum wastage, chemical grouting is competitive with conventional cement, clay, and bentonite grouting.

Einstein and Barvenik (1975) state that in many cases the soil voids are so small that they cannot even be economically grouted with chemical grouts having a viscosity close to that of water, if the permeability is less than 10⁻⁴ cm/sec (10⁵ microdarcy), and that this is not a large drawback because impermeabilization of soils with $K \leq 10^{-4}$ cm/sec is usually not necessary. The limitation is more critical in building foundation work.

Table II

Summary of Pertinent Characteristics of Various Stabilization Procedures

Procedure	Stability			Permanency of Treatment	Amenable Soil Types	Construction Considerations					Costs
	Region Of Improvement	Degree Of Regional Improvement	Ability To Obtain Equivalent Substratum CBR (%)			Required Construction and Fragmentation Time	Degree Of Permanent Disruptions	Disruption To Runway Use	Special Equipment Requirements	Special Considerations	
ELECTRICAL METHODS Electro-Osmosis Electro-Chemical	STABILITY GRADIENT (Decreasing with distance from cathode region.)	VERY LOW TO LOW (Possible stability reduction in cathode region.)	No	Some permanent strength increase	Fine-grained soils (silt and clays)	Very Long	MODERATE (Depends on electrode spacing)	Substantial	1. Electrical power source 2. Dewatering electrodes 3. Electro-Chemical power source 4. Sacrificial electrodes	SAFETY (Shielding of cables and electrodes, protective wear)	VERY HIGH (Large power consumption per cubic yard)
	STABILITY GRADIENT (Variable with chemical type, treatment time, etc.)	LOW (Depends on type of chemical grout and total amount of grout used.)				Long					
CHEMICAL GROUTING	ZONE IMPROVEMENT (Depends on permeability of soils)	MODERATE TO VERY HIGH (Depends on type of chemical grout and total amount of grout used.)	Feasible	Permanent	Minimum drillable granular soils (D ₅₀ -D ₁₀₀) (Depends on type of chemical grout.)	Moderate	MODERATELY HIGH (Requires relatively close grout hole spacing)	Substantial	Pressure grouting equipment, Special equipment required to handle certain chemicals	Control of gel time. Possible blow outs or feed back at high pressure	25-100 dollars/cubic yard of treated material.
CEMENT GROUTING	ZONE IMPROVEMENT (Depends on permeability of soils)	HIGH TO V. HIGH (Depends on w/c ratio, additives and total amount of grout injected)	Feasible	Permanent	For injection: Dig of soil > 1.6-2.0 mm For mixed in place: Feasible. Possibly all fine-grained soils	Moderate	For injection: MODERATE For mixed in place: HIGH	Substantial	For injection: Pressure grouting equipment	For injection: Possible blow outs or feed back at high pressure	For injection: 8-15 dollars/cubic yard of treated material.
LIME PROCEDURES Drilled Hole Pressure Injected	ZONE IMPROVEMENT (Zone size increases with time)	MODERATE TO HIGH (If soil is lime reactive)	Feasible	Permanent	Any fine-grained soil with greater than 10% clay	Moderate	Drilled hole: HIGH Pressure injection: MODERATE	Substantial	For injection: High pressure grouting equipment	For injection: Possible blow outs or feed back at high pressure	Drilled hole: 1.50-7.50 dollars per hole For injection: 0.50-1.00 dollars/cubic yard of treated material.

CONCLUSIONS

During recent years, greater fuel consumption and the discovery of oil near Prudhoe Bay, Alaska, have warranted the need for determining feasible cold weather construction engineering methods as well as seeking adequate engineering materials to utilize under such conditions. This report has reviewed various types of grouting materials in seeking a material which possesses properties that may be of value in cold environments or under low temperature conditions.

The low ambient temperature conditions affect the setting or gel properties of grouts, even though freezing may have little effect on some of the gelled products. Where a low viscosity material is essential for grouting of fine soils, there was no information found that related the effects of temperature to viscosity, and throughout the literature search, freeze/thaw data were not evident.

From the many grout properties reviewed, there was only one type of grout (epoxy resin) found that would harden in a below freezing temperature (20°F) environment. Nevertheless, other low temperature properties/advantages were lacking.

In instances where the ground may consist of surface dry frozen materials or be of high/low ice content, the grout material may have adverse affects on these conditions upon application or during the setting or gelling of the product. With many of the grouts reviewed, there was indication of applicability to moist conditions, but only one was referenced to be applicable under a water table, as might be the case in a thawed situation. However, Karol (1968) indicates that in most applications chemical grouts are placed into saturated or partially saturated formations and gives good laboratory illustrations of what might be the results of placing grout materials below water tables.

This report has reviewed literature on the subject of grouting. It has not produced enough beneficial information relating to the conditions which may be encountered in cold regions to be of any great assistance therein. However, the information compiled has given us general knowledge of various grouting materials and of accomplishments made in research on the subject of grouting soils. Nevertheless, none of this information/data can be reliably compared due to the inconsistency of controlled conditions and types of tests. It was also not evident that cold environments were of concern.

Table III, extracted from TM 5-818-6/AFM 88-32 (DA/AF 1970), gives characteristics or properties of various chemical type grouts. It would be interesting to know what the data would reveal from tests performed in the temperature range from 40°F and below. Temperature ambients or conditions are not indicated in this table.

TABLE III. PHYSICAL PROPERTIES OF
CHEMICAL GROUTS

Class	Example	Viscosity Centipoise	Gel Time Range, min	Unconfined Compressive Strength, psi
Precipitated grouts:				
Silicate (low concentration)	Silicate-bicarbonate	1.5	0.1-300	Under 50
Silicate (high concentration)	Silicate-formamide (Siroc)†	4-40	5-300	Over 500
Chrome lignin	Silicate-chloride (Joosten)	30-50	0	Over 500
	TDM	2.5-4	5-120	50 to 500
	Terra Firma††	2-5	10-300	Under 50
	Blox-All†	8	3-90	Under 50
	Lignosol††	50	10-1000	--
Polymerized grouts:				
Vinyl polymer	AM-9§	1.2-1.6	0.1-1000	50 to 500
Methylol bridge polymer	Urea formaldehyde	6	5-300	Over 500
	Herculox†	13	4-60	Over 500
	Cyanaloc 62§	13	1-60	Over 500
	Resorcinol-formaldehyde	3-5	--	Over 500
Oil-based unsaturated fatty acid polymers	Polythixon FRD	10-80	25-360	Over 500
Epoxy resin	62E2§§	2-18	--	Over 500

† Diamond Alkali Company

†† Intrusion Prepakt, Inc.

‡ Halliburton Company

†† Lignosol Chemical, Ltd.

§ American Cyanamid Company

§§ George W. Whitesides Company

RECOMMENDATIONS

Based upon the search for information compiled for this report, in order to obtain cold environment setting or gel data on the available grouting materials, it is recommended that the following task be undertaken:

1) Synthesis of experience: In order to develop sufficient information on grout materials at low ambient temperatures (40°F and/or below), various grout material manufacturers, agencies, and organizations interested in cold weather grouting construction should be located and contacted and a compilation of their interests and experiences made, including such information as field injection problems and cost effectiveness.

2) Laboratory test: Information has not been found on the effect of low ambient temperatures (40°F and/or below) on the properties of various grouting materials. Various manufacturers should be contacted to obtain representative samples of their products to conduct laboratory tests to determine, among others, setting or gel properties at low ambient temperatures. A detailed documentation (data format) should be made of the results of each sample tested, including an analysis of the advantages and disadvantages for cold weather environments.

3) Field evaluation: Based upon the result of the above laboratory test, a test site of sufficient size and material as well as the proper (concerned) environment should be chosen for an adequate number of field tests, to be conducted to validate the laboratory results. This would allow an in-depth evaluation of injection or grouting procedures and materials.

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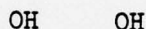
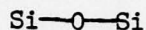
APPENDIX A: CHEMICAL GROUTS

Some chemical grouts and sources of supply are listed below.

Type	Trade Name	Manufacturer, Producer, or Distributor
Acrylamide	AM-9	American Cyanamid Co.
Acrylamide	PWG	Halliburton Oil Well Cementing Co.
Resin	Cyanaloc	American Cyanamid Co.
Resin	Herculox	Halliburton Oil Well Cementing Co.
Silicate	Injectrol-G	Halliburton Oil Well Cementing Co.
Silicate	Siroc	Raymond International, Inc.
Lignin	Blox-All	Halliburton Oil Well Cementing Co.
Lignosulfonate	Terra Firma	Concrete Chemicals Co.
Epoxy resin	--	George W. Whitesides Co.
Polyester resin	--	American Cyanamid Co.
Polyphenolic polymer	Terranier	Rayonier, Inc.
Resorcinol-formaldehyde	CR-726	Catalin Corp. of America
Phenoplast or resorcin-formol	--	Soletanche
Aluminum octoate	Firmgel	Byron Jackson, Inc.
Cationic organic-emulsion	SS-13	Brown Mud Co.
Aminoplasts or urea-formols	--	--
Epoxy-bitumen	--	--
Calcium acrylate	--	--
Aniline-furfural	--	--

To help understand the structure of various grouts substances, much as a chemist would, a network diagram (Fig. A1) taken from Grouts and Drilling Muds in Engineering Practice (1963) illustrates and gives guidance.

In spite of the apparent disparity between the different substances, they all had something in common. With cement, one was essentially concerned with the formation of structure through interlocking crystals created during the setting process. With pure clay grouts one was concerned with very much weaker bonds for forming a house-of-cards structure but, just as in the case of cement, what was being developed was some sort of rigid structure. With the silicate systems there was a reaction giving three-dimensional network structures of the form



With newer materials, the phenoplast type resins and the vinyl resins of the AM-9 type, there was a similar situation. There were aromatic compounds containing hydroxyl groups which started to link through OH's to give again a chain and eventually network structures and to give methylene bridges. With resins of the AM-9 type vinyl compounds were used which could be polymerized in the presence of a catalyst to long chains. This gave some indication of the commonality which existed among all these grouting systems.

